Indian J. Phys. **82** (5), 497-504 (2008)

Use of low energy accelerators

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I first thank the organisers of the PANE conference for giving me the opportunity to talk to you. I feel privileged to give the Bipinpal Das Memorial Lecture of the conference. Prof. Das was an eminent educationist of high intellectual calibre known for his idealism and selfless sacrifice. If the teachers and students today need a role model Prof. Bipinpal Das would be an ideal candidate.

For nearly a century ion beams have been accelerated to different energy regimes to tackle variety of problems in physics. The entire energy range can be broadly divided in three regions: Low, Medium and High energies. We shall assign the values of energies to these regions as follows:

Low Energy	:	0 - 1 MeV
Medium Energy	:	1-1000 MeV(1 GeV)
High Energy	:	> 1 GeV

Accelerators of higher and higher energies have been built over the years to probe first into the structure of the nucleus, then that of the nucleons. Many ground-breaking discoveries in particle and nuclear physics, astrophysics, atomic and molecular physics, condensed matter physics, biomedical physics, medicine, biology, and industrial processing testify the impact of the accelerator developments. In this lecture some of the current work in physics with ion beams at low and medium energies will be reviewed.

Why do we need high energies? High energies act in two ways. One is their ability to impart energy to the system under study and excite various degrees of freedom, and second is that they provide a snapshot of the inside of the system with resolution depending on their energy in analogy to studying objects with a microscope. The spatial resolution that can be achieved depends on the momentum of the particle through the de Broglie wavelength associated with the particle. The wavelength associated with an electron and a proton is given in Table 1 as a function of the particle energy.

Table 1 The associated wavelengths of electron and proton at various energies

Energy	Wavelength of an electron	Wavelength of a proton
eV	2×10^{10} m	$4\ 4 \times 10^{12}$ m
MeV	$1\ 4 \times 10^{13}$ m	$4\ 4 \times 10^{15}$ m
GeV	2×10^{16} m	$1\ 1 \times 10^{16}$ m
TeV	6×10^{18} m	2×10^{19} m

Particles accelerated to high energies are required to explore the dynamics of systems with high binding energies Energies associated with chemical reactions are usually a few meV, with atoms in the range of few eV to few keV, with nuclei in the range of MeV and with "elementary particles' in the range of GeV

All accelerators use electric fields in which charged particles are accelerated The electric fields are used over most of the available frequency range from static fields to ac magnetic fields oscillating at 50 -60 Hz and extending to RF fields in the MHz to GHz range New ideas are being developed to use laser beams to generate even higher electric fields for particle acceleration

Every accelerator has a particle source or injector followed by the main accelerator The sources for positive ions are usually one of the following glow discharge, ECR plasma and sputter source The goal for heavy ions is to maximise the charge state before injection into the main accelerator Electrons are commonly generated from a heated filament or an indirectly heated cathode Very short pulses of electrons can be generated using a powerful laser directed at a photocathode Anti-particle beams are generated through the interaction of high-energy particles with energy >> $2mc^2$, where m is the rest mass of the particle The flux, *i e*, the number of particles incident per unit area of particles depends on the yield of the ion source and the emittance of the beam Since the flux decides the type of physics problems that can be addressed, considerable effort has been given for increasing this quantity by beam cooling techniques

Then comes the main accelerator, which could be of several types, both electrostatic or electromagnetic The different categories of accelerators are shown in figure 2 Electromagnetic field in vacuum does not accelerate particles directly There are two reasons for this, (i) E vector of the plane wave in free space is normal to the direction of propagation and (ii) the wave velocity is c, thus even if we could turn E vector in the direction of propagation, the particles would not remain in phase with the wave The wave changes its phase as it overtakes the particle and the net effect is zero There are two ways of getting around this difficulty One solution is to slow down the electromagnetic wave in a suitable structure or medium and let the particles go in a straight line The second solution is to bend the particles and let the electromagnetic wave travel as in free space All accelerators can be classified into one of these categories

In the linear electrostatic machines, the electric field is provided by the high voltage is generated either using a cascade multiplier circuit or a belt/pellet charging system

Among the RF machines we have one group that can be classified as resonant system and the other non-resonant. Linear accelerators using resonant cavities, cyclotrons and synchrotrons come under this category. Linear induction accelerators and circular betatrons can be classified as non-resonant RF accelerators.

Before we proceed further, let us take a look at the limits of these machines and the reasons for the limits. The energy gain in linear accelerators is determined by the electric field and the length of the accelerator. The maximum voltage reached in electrostatic machines is 25-30 MV, determined by the breakdown limit of insulation gas medium. For resonant cavities, the field limit is set by the field emission of electrons and is close to ~100 MV/m. This limit has nearly been reached in laboratory tests for superconducting niobium cavities operating in the GHz region. However, no existing accelerator as yet operates at this limiting accelerating fields. Thus for the length scales of few km we expect the energy gain in linacs to be in the range of 100 GeV. In cyclic accelerators, the energy gain is determined by the magnetic fields required to keep the particles in orbit and the size of the machine is governed by the radius. As we reach the regime of relativistic energies, the energy available in the centre of mass system increases only as the square root of the beam energy for stationary targets. This is where the colliders score over fixed target machines. For a collider, the energy available is the sum of the energies of the two particles. With superconducting magnets and a radius of ~10 km the highest energy achievable is ~ 1000 TeV. But emission of synchrotron radiation limits the useful energy for electrons to ~ 100 GeV and for protons to ~ tens of TeV. The highest energy lepton accelerator was the 100 GeV electron- positron collider at CERN(LEP) and for hadrons the 1 TeV proton-antiproton collider at Fermilab(Tevatron) provides the highest energy. The 7 TeV large hadron collider(LHC) at CERN is the highest energy accelerator to be built so far, and will be commissioned at the end of 2007. The next high energy machine being planned is the International Linear Collider, in which electrons and positrons will be accelerated to 500 GeV each first and then upgraded to 1 TeV each.

The ever-increasing size of accelerators has now reached both the physical and financial limits. Thus, totally revolutionary concepts in generating high electric fields are required. Would it be possible to use the high crystal fields (10^{17} eV/cm or 10^{10} GeV/m) present in solids although they exist over very small distances? Hopes for the future have come from the investigations being carried out in laser-plasma interactions. Extremely high fields (100 GeV/m) has been generated over lengths of few mm in relativistic plasma waves driven Raman forward scattering instability induced by short, high-intensity laser pulses. Accelerated electrons upto 44 MeV have been detected from early experiments in this field at Rutherford Appleton laboratory[2]. Other laser driven plasma accelerator schemes are the Plasma Wakefield accelerator and the Plasma Beatwave accelerator.

Where are we in India in the accelerator scenario? All our accelerators address the low energy regime. Currently the accelerator facilities in India include,

14UD Pelletron at TIFR, Mumbai with superconducting booster Linac [3]

15UD Pelletron at NSC, Delhi, with superconducting booster Linac [4]

K=140 Variable Energy Cyclotron at Calcutta and the K = 500 superconducting cyclotron [5]

700 MeV electron synchrotron feeding a 450 MeV storage ring INDUS-I at RR CAT Indore and a 2 5 GeV storage ring INDUS-II [6]

3UD Pelletrons at Bhubaneswar [7] and 3 MV Tendctron at Hyderabad [8],

1 7 MV Tandetrons at, IIT, Kanpur [9] and Kalpakkam [10],

7 MeV cyclotron at Chandigarh [11]

5 5 MV Van de Graaff at BARC converted into a 7 MV folded tandem [12],

8 MeV electron microtrons at Pune [13] and Mangalore [14]

With superconducting booster upgrades at Mumbai and Delhi, Superconducting Cyclotron at Calcutta and the INDUS-II at Indore we shall continue to address low energy physics problems in Nuclear and Atomic Physics, Condensed Matter and Materials Science

World-wide the scenario for Nuclear Physics is moving towards research with radioactive ion beams and relativistic heavy ion collisions High brightness synchrotrons are being used for condensed matter and atomic physics research Many smaller accelerators have now entered the industries and there is a growing market for these machines In the higher energy regime efforts are being put to develop high current GeV proton machines for applications for energy production, radioactive waste transmutation and spallation neutron sources

Let us now take a look at the impact of accelerators on fundamental research first and then we shall turn our attention to the applications in industry and medicine

Particle Physics

The development of particle physics has been intimately connected with the availability of particle accelerators of high energy Some of the important milestones associated with accelerators are

Discovery of antiproton at Berkeley Bevatron in 1955

Two neutrinos at AGS, Brookhaven in 1962

Discovery of CP violation in K decay at Brookhaven, 1964

Neutral current at CERN proton synchrotron, 1972

Discovery of J/s at AGS, Brookhaven and Stanford Linear Collider, 1974

Discovery of b quark, Fermilab, 1977

Discovery of W and Z with SPS collider, CERN, 1983

Discovery of top quark, Fermilab and LEP, CERN, 1995

Now accelerators are probing structures of matter with ever-increasing resolutions

Nuclear Physics

As we have noted earlier, the accelerators were first built to study the nucleus and these have been an essential tool ever since the first machines were built They have been used to probe structure of nuclei at different energy and angular momentum states and far from the lines of stability. The energy levels of a large number of nuclei have been determined showing a rich variety of phenomena from backbending, superdeformation, shape coexistence, *etc.* The question of how the strong force binds nucleons together in nuclei is fundamental to the very existence of the universe. From the first few minutes of the "Big Bang", the mutual interactions of nucleons to form nuclei and their further accretion to form heavier nuclei, has been crucial in shaping the world we live in Recent experiments with accelerators at Berkeley and Dubna have shown evidence for the unusual stability of superheavy nuclei. Manifestations of subnucleonic degrees of freedom in nuclei are being searched using medium energy electron and proton accelerators Relativistic heavy ions are being used to probe the possible quark-gluon-plasma phase of matter

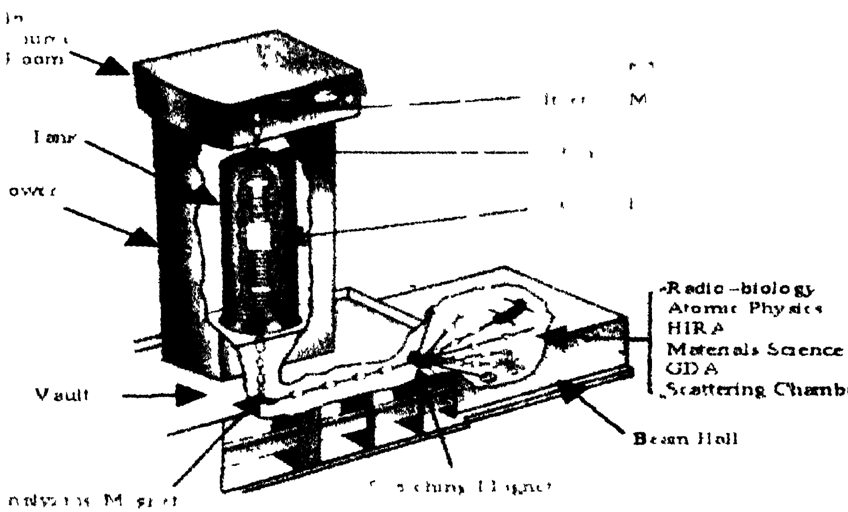

Figure 1. Schematic of the 15 UD Pelletron accelerator facility at IUAC with 7 beam

The facilities available for nuclear physics research are Gamma Detector Array, Recoil-distance device, Mini-orange spectrometer, Charged-particle array, Neutron Array, Heavy Ion Reaction Analyser, Hybrid Recoil Analyser, Indian National Gamma Array, Light Radioactive Ion Beam(e.g , 7Be). The schematic of the accelerator system at IUAC is presented in Figure 1 and the first module of superconducting linac booster in Figure 2.

Cosmology and Astrophysics

Accelerators with higher and higher energies are providing information about the state of matter in the universe at early epochs At 100 GeV equivalent of energy the time scale is 10^{10} s from the origin in a hot "big bang" model of the universe. Results obtained with

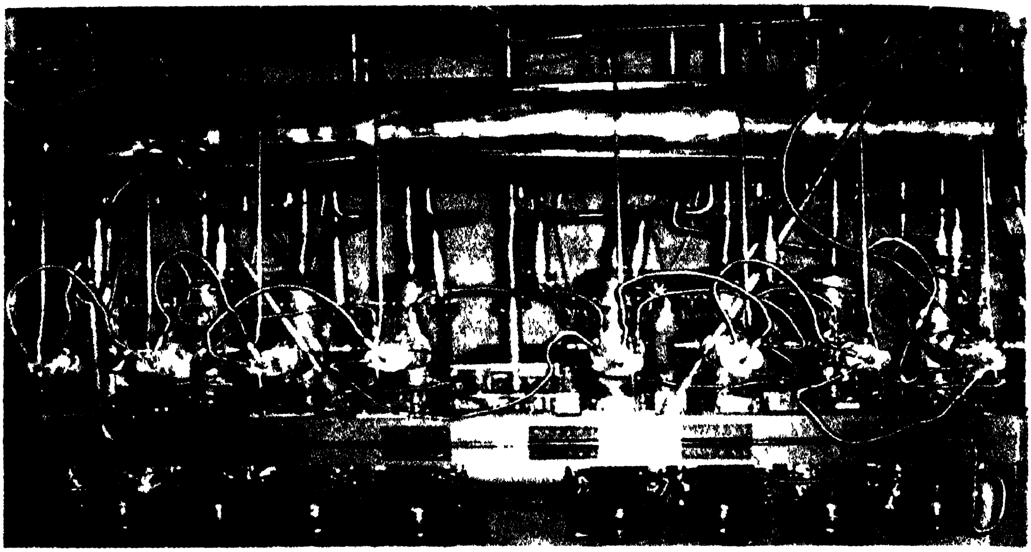

Figure 2. Eight Quarter Wave Nb resonators mounted in the first linac module at IUAC

accelerators on nuclear reaction cross sections allow the observed H/He ratio to be explained. The determination of the rates of nuclear reactions occurring inside stars and supernova are crucial for understanding of the synthesis of elements. In the coming years the advent of radioactive ion beams are going to provide direct measurement of the relevant cross sections.

Atomic Physics

The mechanism of atomic collisions and ionisation processes is still not sufficiently understood. Accelerators are being used in many laboratories towards measurement of electron and photon emissions, charge exchange cross sections, energy loss processes in atomic collisions. Many of these phenomena are important in understanding of plasma processes in tokamaks and dynamics of stellar atmosphere. Radiation from synchrotrons is also used for atomic and molecular studies. These types of studies are also important to chemistry and biology, not only in understanding of reaction processes, but also in determination of structures.

Condensed Matter and Materials Science

Condensed matter and materials science also benefited enormously from accelerators Synchrotron radiation from electron machines has become a major tool for determination of structure of materials using the technique EXAFS. Neutron diffraction studies have taken a giant leap forward with intense beams being available from spallation neutron sources driven by GeV protons. Ion beams are used in a host of techniques with acronyms like RBS(Rutherford Backscattering), ERDA(Elastic Recoil Detection Analysis), PIXE(Proton Induced X-ray Emission), NRA(Nuclear Reaction Analysis), SIMS(Secondary Ion Mass spectrometry), PDMS(Particle Desorption Mass Spectrometry), AMS(Accelerator Mass Spectrometry).

Use of swift heavy ions (SHI) from heavy ion accelerators in material modification is throwing new light on relaxation mechanisms in solids in time scales of nanosec to picosec Large changes in critical currents have been observed in high temperature superconductors on SHI impact The transition temperature is significantly modified for materials showing Colossal magnetoresistance

The facilities available for materials science research are UHV Scanning Tunnelling Microscope, Elastic Recoil Detection Analysis, Three-axis Goniometer, In-situ X-ray reflectivity, In-situ photoluminescence, Atomic Force Microscope, Low Temp Cryostat with 8T magnet, In-situ X-ray Diffractometer The in-situ XRD set-up at IUAC is presented in Figure 3

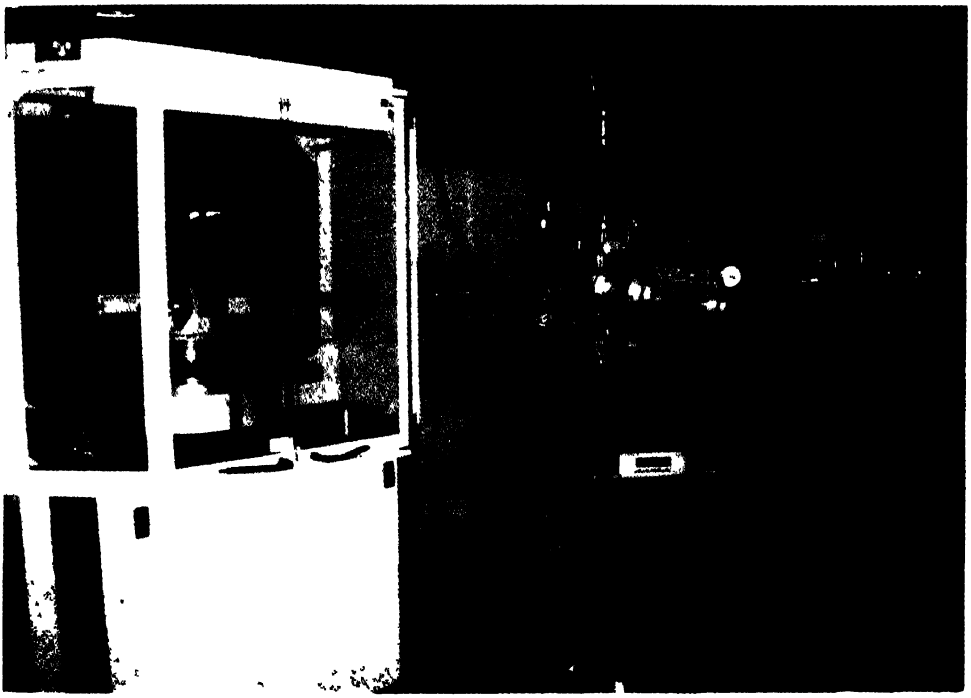

Figure 3 *In-situ* XRD set up in beam line after the booster linac

Accelerator produced ion beams are increasingly being used for studying Single Event Upset mechanisms for electronic circuits These studies are extremely important for space missions, where the circuitry used is subject to bombardment of particle radiation in space

Radiation Biology

Heavy ions are being increasingly used for radiation therapy. They are highly ionizing and the Linear Energy Transfer (LET) for heavy ions are large Also due to the nature of energy loss in materials, most of the energy of a heavy ion is transferred to the medium at the end of its range. This is the Bragg peak region in energy loss of ions. This property is utilized for heavy ion therapy to target specifically tumour cells which can be selectively destroyed with minimum collateral damage to the healthy tissue surrounding it.

The process of interaction of high LET radiation with living cells is far from understood and the studies undertaken in this area are apoptasis, DNA damage and repair. The modifications of genetic material under bombardment of heavy ions are also being pursued at different labs.

Some of the areas of science where important contributions have emerged from accelerator based research in India are, (i) in Nuclear Physics, fusion fission reactions with heavy ions, role of angular momentum in sub-barrier fusion and delineation of the equilibration time for angular momentum degree of freedom in fission reactions Spectroscopy of high spin states and the role of p-n residual interactions in nuclei, neutron emission in pre-equilibrium reactions, (ii) in Atomic Physics, the measurement of inner-shell ionisation and recoil ion spectroscopy, (iii) in Materials Science, flux pinning in high-temperature superconductors, change of transition temperature in Colossal Magnetic Resistance materials.

Among the application of accelerators, the notable ones are: Medical applications, such as diagnosis and treatment of cancer, Mineral and oil prospecting, using neutrons produced with small accelerators, Charged particle beams for processing semiconductor chips, Intense sources of X-rays for sterilization of medical equipment and food products Charged particle beams for materials sciences analysis and radioisotope production Radiocarbon dating and trace element analysis using ion beam induced radiation techniques

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